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NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
NAVAL AIR STATION, PENSACOLA, FL 32508-5700

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BEHAVIORAL EFFECTS OF HIGH PEAK POWER MICROWAVE PULSES: HEAD EXPOSURE AT 1.3 GHz

J.A. D'Andrea, B.L. Cobb, and
J.C. Knepton, Jr.

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A. J. MATECZUN, CAPT, MC USN
Commanding Officer

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The animals used in this work were handled in accordance with the principles outlined in the *Guide for the Care and Use of Laboratory Animals*, prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animals Resources, National Research Council, DHHS, NIH Publication No. 86-23, 1985; and the Animal Welfare Act of 1966, as amended, 1970 and 1976.

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D'Andrea, J.A., Cobb, B.L., and Knepton, J.C. Jr.

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13. ABSTRACT *(Maximum 200 words)*
To investigate behavioral performance effects of localized exposure to the head of very high-peak-power microwaves, rhesus monkeys (Macaca mulatta) were trained on a vigilance task. The task consisted of responding on one lever for a variable interval (VI 30-s) schedule and then responding on a second lever for food pellet reward. Monkeys were exposed for 25 min to 1.3-GHz microwave energy pulsed at 7, 9, and 11 pps. The pulse duration was 7 μs with a peak power of 3.06 MW. Microwaves were delivered to the posterior of the head by an open-end waveguide irradiator. Average specific absorption rate (SAR) in the head ranged from 16.0 to 35.0 W/kg. The microwave period was preceded by a 25-min preexposure period and followed by a 25-min postexposure period, each separated by a 1-min extinction period. Response rate on the VI lever decreased only at 26.0 and 35.0 W/kg compared to sham exposure sessions. Reaction time and postreinforcement pause were unchanged in the exposed conditions relative to shams.

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SUMMARY PAGE

PROBLEM

Accidental exposure to microwave radiation is possible in many civilian and military occupations. To protect personnel, current microwave safety standards were set for a whole-body specific absorption rate (SAR) of 0.4 W/kg, which is a factor of 10 below the threshold for performance changes in animals (4 W/kg). The animal exposures, however, have been whole-body exposures where the entire body is immersed in a uniform microwave field. Accidental human exposure can involve either the entire body or only part of the body exposed to microwave fields. This was recognized in the safety standards by allowing a maximum localized SAR of 8 W/kg in any 1 g of tissue. This SAR, however, was based primarily on data from experiments measuring the absorption in models of man. The purpose of this study was to determine the effects of localized exposure of only the head to pulsed microwaves on monkey behavior .

FINDINGS

Behavioral alteration was characterized by decrements in response rate but not by changes in reaction time, yellow light errors, and post reinforcement pause time. The threshold SAR for the observed changes was between 16 and 26 W/kg absorbed in the monkey head.

RECOMMENDATIONS

The behavioral threshold range determined in this study for a localized exposure to the head to produce a behavioral effect was 16-26 W/kg, which is well above the 8 W/kg safety standard for localized exposure. However, this localized exposure threshold does not provide a safety factor of 10 as is the case with the whole-body exposure standard.

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INTRODUCTION

Microwave energy is used for medical, industrial, telecommunication, radar, and electronic warfare purposes, just to name a few. Over the last 40 years, the output power of many such devices has increased substantially, which accentuates the concern over inadvertent exposure. Considering the kind and number of microwave devices in use, the possibility of accidental exposure is high in numerous civilian and military occupations.

Present microwave safety standards (1,2) recommend limiting exposure to 0.4 W/kg for a whole-body specific absorption rate (SAR) and 8 W/kg for localized SAR in any 1 g of body tissue. The whole-body standards are based, in large part, on behavioral data from animal models exposed to microwave radiation. Both rats (3,5,6) and rhesus monkeys (4,6) have been exposed to microwaves, and changes in behavioral performance have been documented with threshold effects near whole-body SARs of 4 W/kg. A safety factor of 10 below this threshold is the basis for the 0.4 W/kg maximum permissible exposure. These experiments were, however, conducted with whole-body exposure to microwaves. In the military or civilian workplace, the possibility of exposing part of the body to a microwave emitter such as a cracked waveguide or damaged antenna is very real.

The effects caused by partial body exposure have not received the experimental evaluation that has been devoted to the whole-body exposure case. The recommended localized SAR of 8 W/kg is based largely on measurements of localized absorption in models of man.

In addition, the safety standards do not limit the instantaneous peak power of pulsed microwave fields. Microwave fields with high peak powers but low pulse repetition rates may satisfy the currently accepted safe SAR limits, but the possibility of adverse health effects from pulsed microwaves with very high peak power has caused some concern, especially in military radar and directed energy facilities. For this reason, we evaluated pulsed microwaves instead of continuous wave radiation.

The experiment reported here was conducted to provide information on the threshold for behavioral performance effects of pulsed microwave exposure to the head of the rhesus monkey. The effects were documented using schedule-controlled behavior as has been done with the previous experiments. This study is part of a Navy Department research program to determine thresholds of behavioral effects induced by high power microwave pulses typically produced by Navy radars.

MATERIALS AND METHODS

SUBJECTS

Four male, juvenile rhesus monkeys (*Macaca mulatta*) obtained from the Naval Aerospace Medical Research Laboratory (NAMRL) primate breeding program were used as subjects. The mean body mass of the subjects during the study was 3.55 kg (± 0.09 kg *SEM*). The subjects were fed a standard primate diet (Wayne Co., 24% protein) daily in sufficient quantities (freely available in their cages) to produce a normal-sized animal for that age. Before training, the animals were fed a reduced amount of the same diet daily until their body mass was reduced by 5% of the previously determined ad-libitum weight. During the experiment, the monkeys were maintained near this reduced weight except for periods when they were again free-fed for 5-7 days to establish a new ad-libitum weight. This procedure resulted in healthy, well-conditioned animals that worked adequately on food-reinforced tasks. The animals obtained their daily food ration (Noyes Co., 750-mg monkey formula L pellets) while performing the experiment. Their diet during the experiment was supplemented only with fresh fruit. Animals were housed one to a cage where water was always available. The photoperiod was regulated to 12-h light and 12-h dark (0700 on, 1900 off). Home cage temperature was maintained at 20.2 and 23.5 °C.

APPARATUS

Behavioral

Monkeys were seated in a Plexiglas chair (Fig. 1) and housed within a microwave anechoic chamber. The chair was fitted with two plastic response levers mounted in front of the monkey and within easy reach. Each pull of the lever actuated a microswitch (Microswitch No. V3-619) mounted beneath and out of reach of the monkey. The chamber (2.6 m high X 4.5 m long X 2.7 m wide), was constructed of plywood and lined on the interior surface with sheet metal covered by pyramidal microwave absorbing material. The chamber was lighted with two flood lamps (75 W) and ventilated with room air by a large fan. A wide-spectrum masking noise was produced by a white-noise generator (7) and delivered to the chamber with a small loudspeaker mounted outside of the microwave field. A background noise level of 73 dBA was measured at the styrofoam chair. The behavioral task was controlled by three colored lamps (GE No. 757) mounted behind a plastic light-diffusing screen attached to a Styrofoam stand that was placed 50 cm in front of the monkey at eye-level. A pellet feeder (Foringer 750 mg) mounted inside the chamber delivered food pellets (750 mg, Noyes monkey pellets) to a cup on top of the chair via a 1.0-m length of Tygon plastic tubing. Two closed-circuit TV cameras provided observation of the monkey within the chamber. A telethermometer (Yellow Springs No. 400) was used to record the ambient temperature inside the anechoic chamber. A microcomputer (Zenith Z-248-62) and digital experiment controller (7,8) were used to control the events during the experiment and to record the data. An algorithm written in EBASIC language (7) monitored inputs from the lever microswitches and provided control over the relay circuitry, colored light stimuli, chamber lights, and pellet feeder via the digital control interface. Data were transferred between the digital control interface and the microcomputer via a standard serial communications package (Crosstalk, DCA/Crosstalk, 1987).

Dosimetry

An estimate of the localized SAR of the rhesus monkey was determined using a fresh rhesus carcass euthanized due to illness. Standard metallic temperature probes cannot be used to measure temperature changes during microwave irradiation because they significantly perturb microwave fields. Hence, we used a temperature monitoring system with fiber-optic temperature probes (Luxtron, No. 750). Serial data output from the temperature monitor was recorded for later analysis with a portable microcomputer (Televideo XL) using the Crosstalk communications program.

Average SAR of the whole head of the monkey was also estimated using a saline-filled (400 ml, 0.9% saline) spherical latex balloon model. The balloon (National Latex Products Co. No. K-1537) was approximately the same size (7 cm diameter) as the head of a rhesus monkey used in this study and provided a quick means to check head SAR just before each behavioral test exposure session. Temperature was measured before and after exposure by a standard laboratory mercury thermometer (ERTCO No. 70-17) and an electronic thermometer (Fluke No. 80T-150U).

Microwave Exposure

Pulsed microwave energy was provided by a military radar (AN/FPS-7B) operating at 1.3 GHz. This radar used a klystron (Varian No. L3250) with the internal oscillator triggered by an external source. Radar pulses for this experiment were 7-μs duration with a peak power of 3.06 MW. The pulse-repetition rate of the radar was externally controlled at 7, 9, or 11 pps by two pulse generators connected in series (Data Dynamics 5105 and Hewlett Packard 214A). The radar output was delivered to the chamber via a rectangular waveguide (WR-650) filled with compressed air (2 atmospheres). The waveguide circuit included a directional coupler (General Electric No. CU-597/FPS-7B) to measure power and a waveguide switch (General Electric No. 74251926) to direct microwave energy either to an irradiator or to a water-cooled resistive load. An open-ended waveguide (WR-650) served as the irradiator and was mounted in the

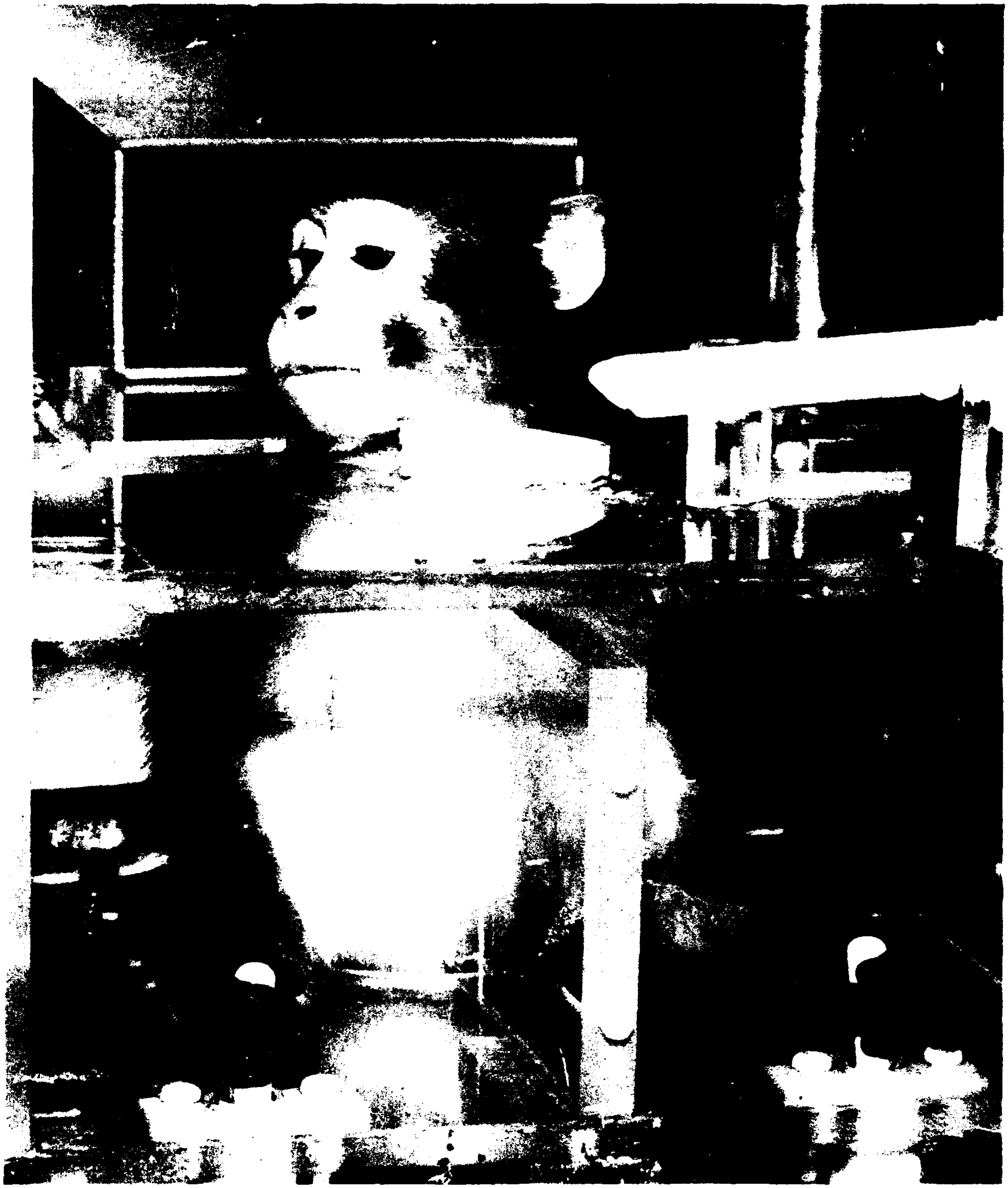

Figure 1. *A rhesus monkey sitting in the Plexiglas chair. The open-ended waveguide irradiator can be seen behind the monkey's head.*

anechoic chamber with a vertically polarized electric field. During training and microwave exposures, the monkey was seated in the chamber with the center of the monkey's head 7 cm from the end of the waveguide irradiator (see Fig. 1).

PROCEDURE

Behavioral

The monkeys were placed on restricted food rations and then trained by successive approximation to operate two levers for food pellet reward. This task, diagramed in Fig. 2, required the monkey to respond on one lever in the presence of a red light. The first response on this lever at the end of a variable time interval (30 s average, 2-140 s range) turned off the red light and turned on either a green light (75% of the trials) or turned on a yellow light (25% of the trials). The green and yellow lights were illuminated for 1 s. A response on a second lever while the green light was illuminated resulted in a food pellet reward. A response on the second lever in the presence of an illuminated yellow light was followed by a 30-s time out with the anechoic chamber lights and the stimulus panel lights (red, green, yellow) turned off. The sequence of red light responding followed by either a yellow or green light was typically repeated 100-120 times in a single behavioral test session. The behavioral session lasted 77 min and consisted of three 25-min components separated by 1-min extinction periods. During the extinction periods, the levers were ineffective, and all lights were turned off. Microwave exposures were always given during the middle 25-min component allowing three distinct behavioral evaluations: premicrowave, microwave, and postmicrowave.

Dosimetry

The rhesus monkey carcass was mounted in the Plexiglas chair and positioned in the anechoic chamber to simulate behavioral test sessions. Four temperature probes were inserted into the carcass at various depths followed by microwave exposure at 9 pps for 180 s. Small holes were drilled in the back and top of the skull and small plastic cannulae inserted into the brain. Two locations along the vertical central axis and one along the horizontal central axis of the cranial cavity in the head were sampled at 10, 16, and 26 mm as measured from the surface of the brain. The fourth sample site was the center of the neck. Tissue temperatures were recorded every 10 s before, during, and after exposure to microwaves. Identical measurements were made after two different microwave exposures. The local SAR was calculated using the following formula:

$$\text{SAR (W/kg)} = 4.186cT/t$$

where T is the temperature change in degrees Celsius, c is the specific heat for brain tissue in cal/g/°C, and t is the exposure time in seconds.

Average SAR of the whole head was estimated with the saline-filled balloon by measuring the temperature of the saline and quickly placing it on the Plexiglas restraint chair in the location of the monkey's head and irradiating it for 180 s. The balloon was then quickly agitated to provide mixing, the temperature was remeasured, and the SAR was calculated using the formula given above.

Microwave Exposure

Following the development of stable behavioral performance on the schedule, the monkeys were exposed with the long axis of the body parallel to the electric field vector (E||L). Microwave pulses (7-μs duration) were given at pulse repetition rates of 7, 9, and 11 pps. A repeated-measures experimental design with subjects tested under all conditions was used where the order of the various exposures and a sham exposure were given randomly for each monkey. During a sham exposure session, the radar was operational,

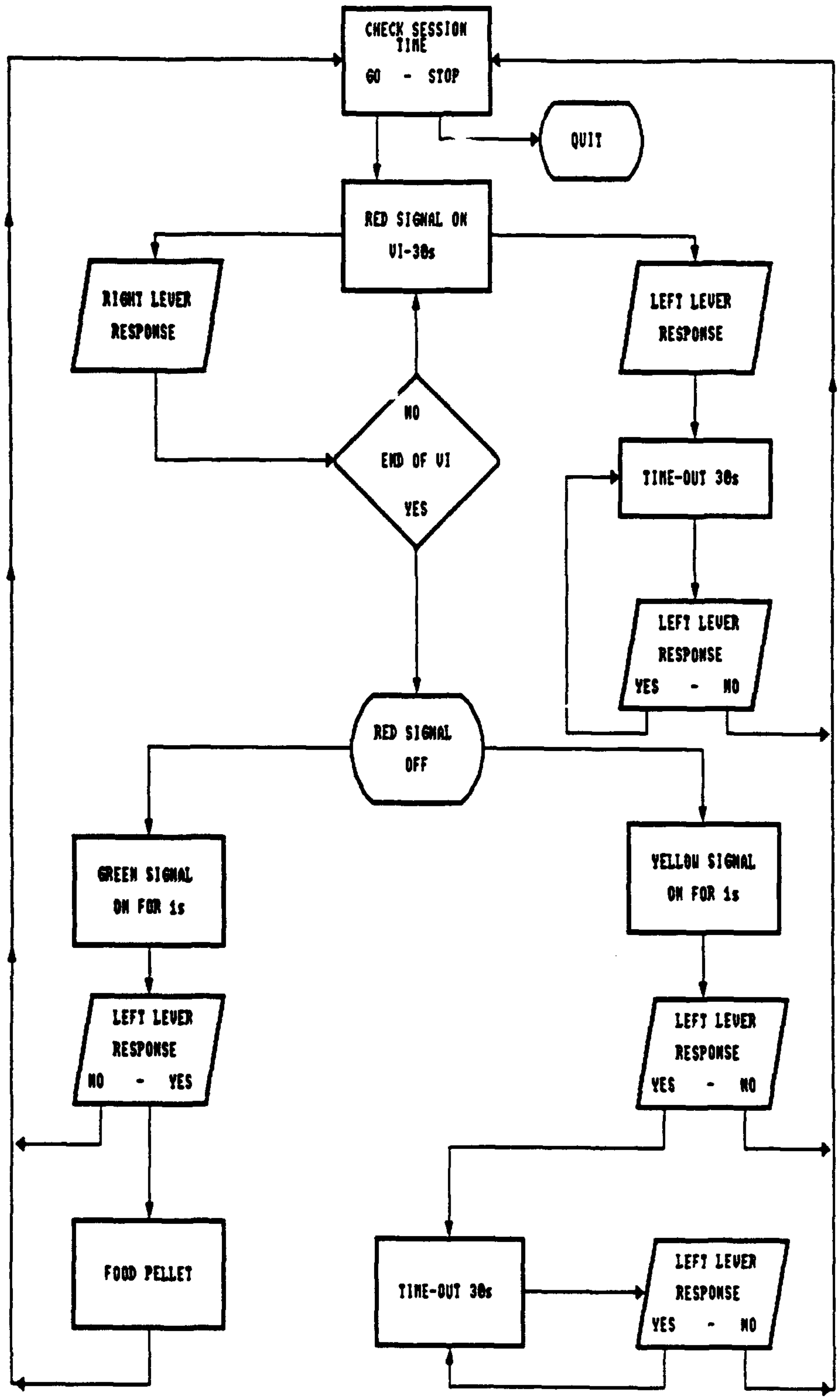

Figure 2. *Schematic diagram of the behavioral task performed by monkeys during microwave and sham exposures.*

but the microwave energy was redirected from the waveguide irradiator to the resistive load using the waveguide switch.

A completely within-subjects analysis-of-variance (ANOVA) design (9) was used to evaluate the effects of the different exposure conditions on four measures of behavioral performance; response rate during red light, reaction time during green light, number of responses to a yellow light, and postreinforcement pause time. Each ANOVA was followed by pairwise post-hoc comparisons of all means from each behavioral measure. Minimum level of significance for the ANOVAs and post-hoc tests was set at a probability level of 0.05. Also, a Pearson product moment correlation coefficient was calculated for SAR and response rate (red light).

RESULTS

DOSIMETRY

As measured by the balloon model, we estimated that the exposures at 7, 9, and 11 pps produced average SARs in the monkey head of 16.0, 26.0, and 35.0 W/kg, respectively. The localized SARs in the four sites sampled in the head and neck of the monkey carcass at 9 pps are illustrated in Fig. 3 and show that highest absorption was near the back surface of the head at 26.58 W/kg.

BEHAVIORAL

A typical cumulative record showing responses before, during, and after microwave exposure at 11 pps (Monkey 3N44) is shown in Fig. 4. The mean response rate on the red light lever is shown in Fig. 5 as a percent of control where the session the day before exposure served as the control. Sham exposures had no significant effect on VI response rates, whereas microwave exposure significantly decreased in response rate ($F(1, 3) = 113, p < 0.002$). Post-hoc tests showed significant differences between sham and microwave exposures at 9 and 11 pps ($p < 0.05$). Response rate was negatively correlated with SAR of the head ($r = -.77, p < .05$). As shown in Fig. 6, recovery of response rate occurred during the postexposure period of the session for microwave exposures at 7 and 9 pps but not for exposures at 11 pps.

The mean reaction time to the green food signal is shown in Fig. 7 as a percent of control where the session the day before exposure served as control. Microwave exposure had no effect on reaction time. Likewise, very few responses during the yellow light were emitted. In addition, postreinforcement pause time was essentially equal between sham and microwave exposure sessions.

DISCUSSION

Behavioral alteration was characterized by decrements in response rate but not by changes in reaction time, yellow light errors, and postreinforcement pause time. There are two distinct explanations for the singular effect of microwave pulses on response rate. First, the reduction of response rate may be due to an auditory sensation during microwave exposure and subsequent distraction of the animal from producing the normally consistent rates of responding during the red light. People have reported a hearing effect produced by pulsed microwaves. An early report described the effect as "clicks" or "hissing" located behind the head (10), that required pulsed energy for its occurrence. Several important studies have verified the hearing sensation (11) and measured cochlea microphonics produced by pulsed microwaves (12). Foster and Finch (13) suggested that the hearing effect was due to a thermoelastic expansion of tissue during absorption of a microwave pulse with a subsequent thermoacoustic pressure wave propagating through tissue producing the hearing effect by stimulating receptor cells located within the cochlea of the ear. It is reasonable to assume that the energy delivered to the head of our monkeys was well above the threshold for the hearing effect (14).

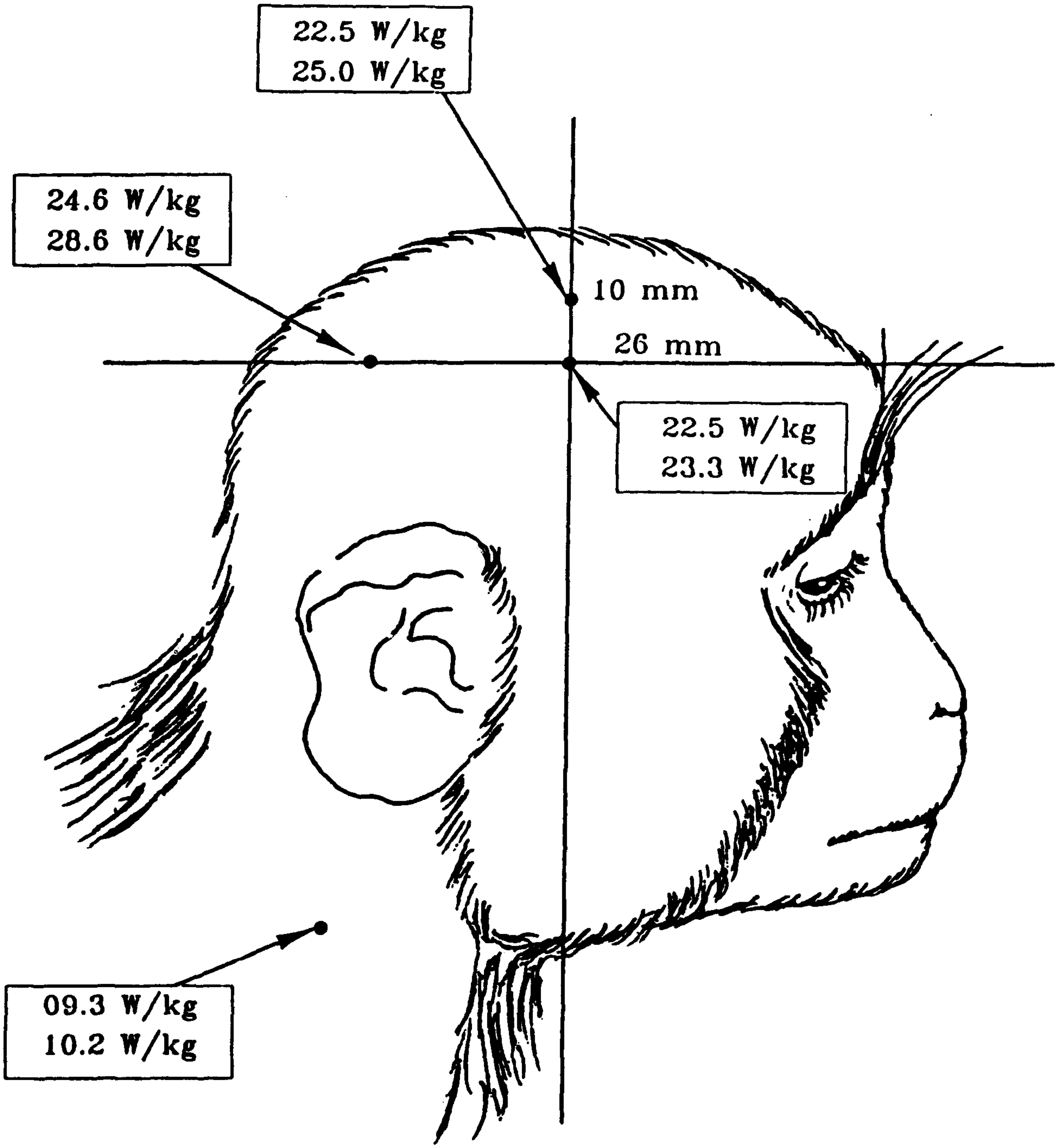

Figure 3. *Specific absorption rate at various sites in the head and neck the monkey carcass exposed to 9 pps.*

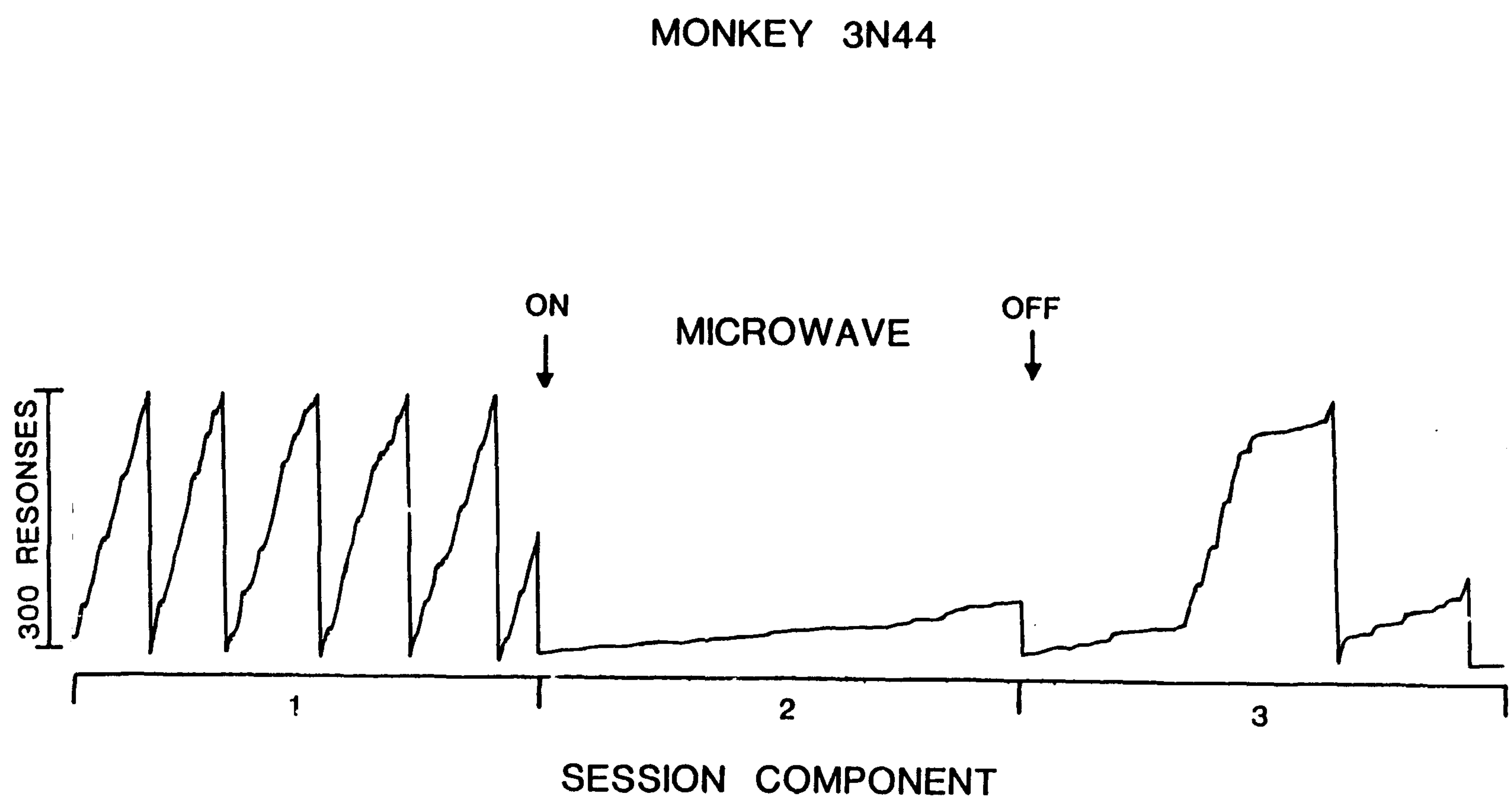

Figure 4. *Typical cumulative record showing responses on the right lever during session components 1 (preexposure), 2 (microwave exposure at 11 pps), and 3 (postexposure).*

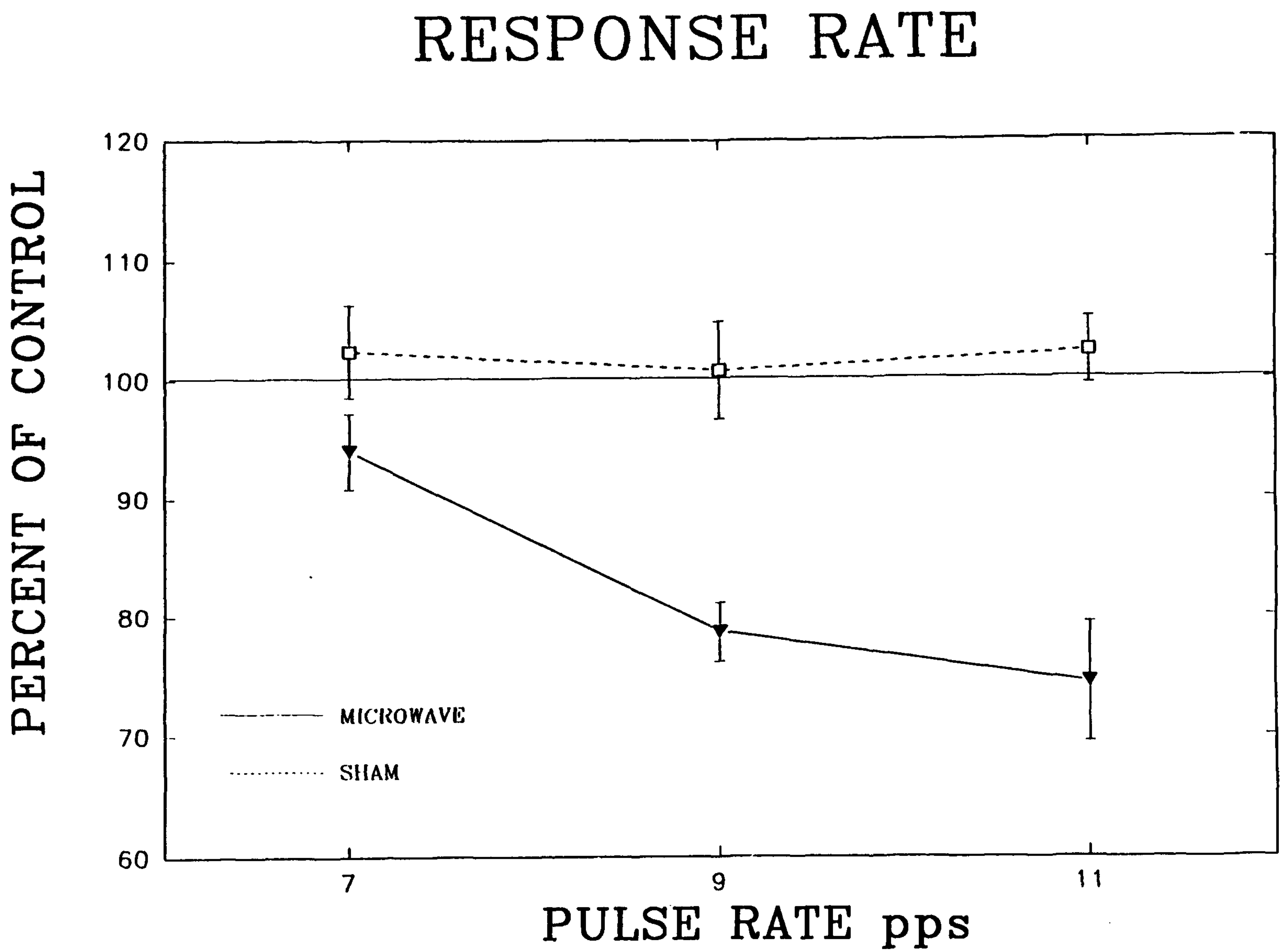

Figure 5. *Mean response rate (± SEM) as a percentage of baseline response rates.*

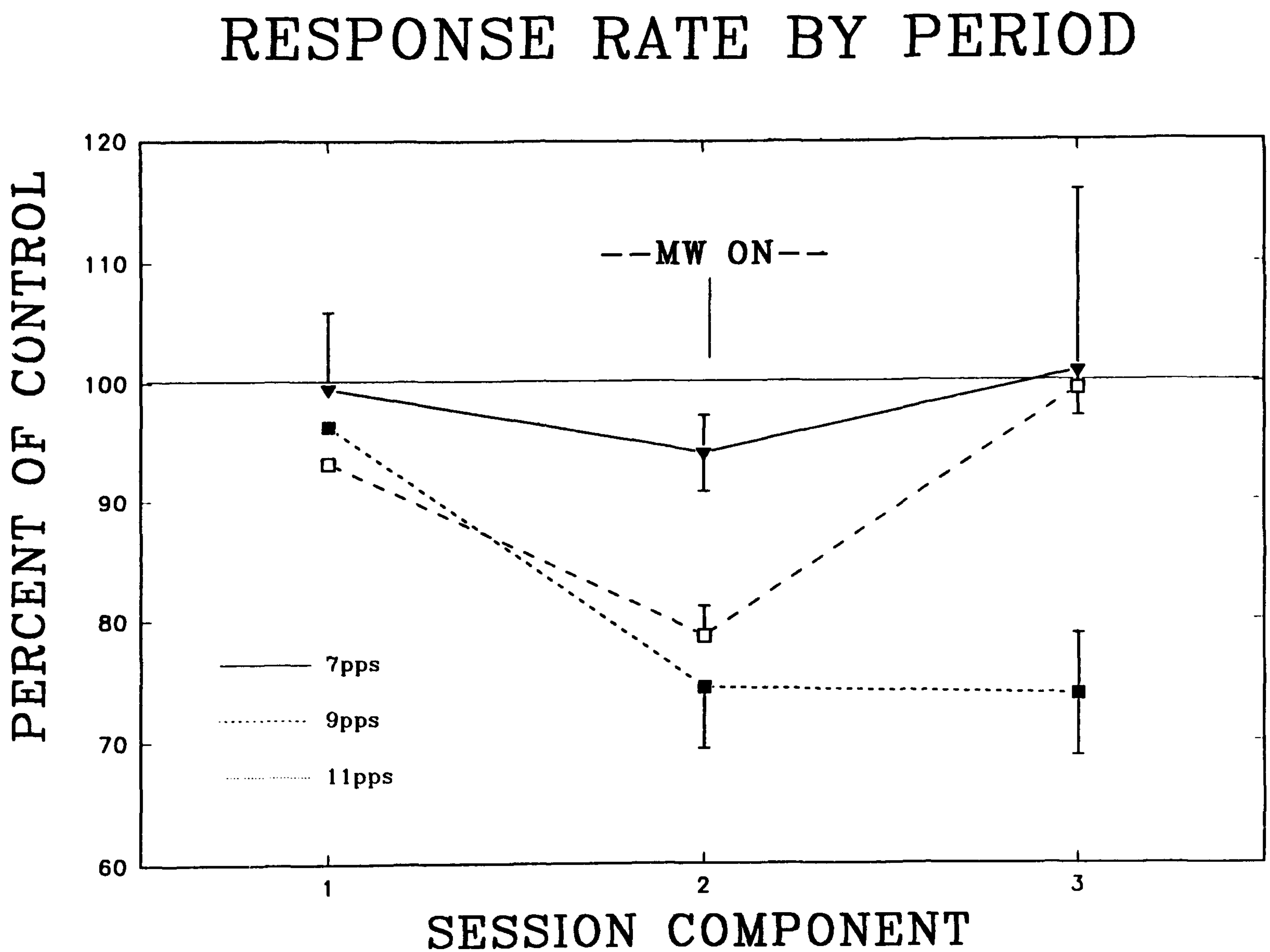

Figure 6. *Mean response rate (± SEM) for each session component as a percentage of baseline response rates.*

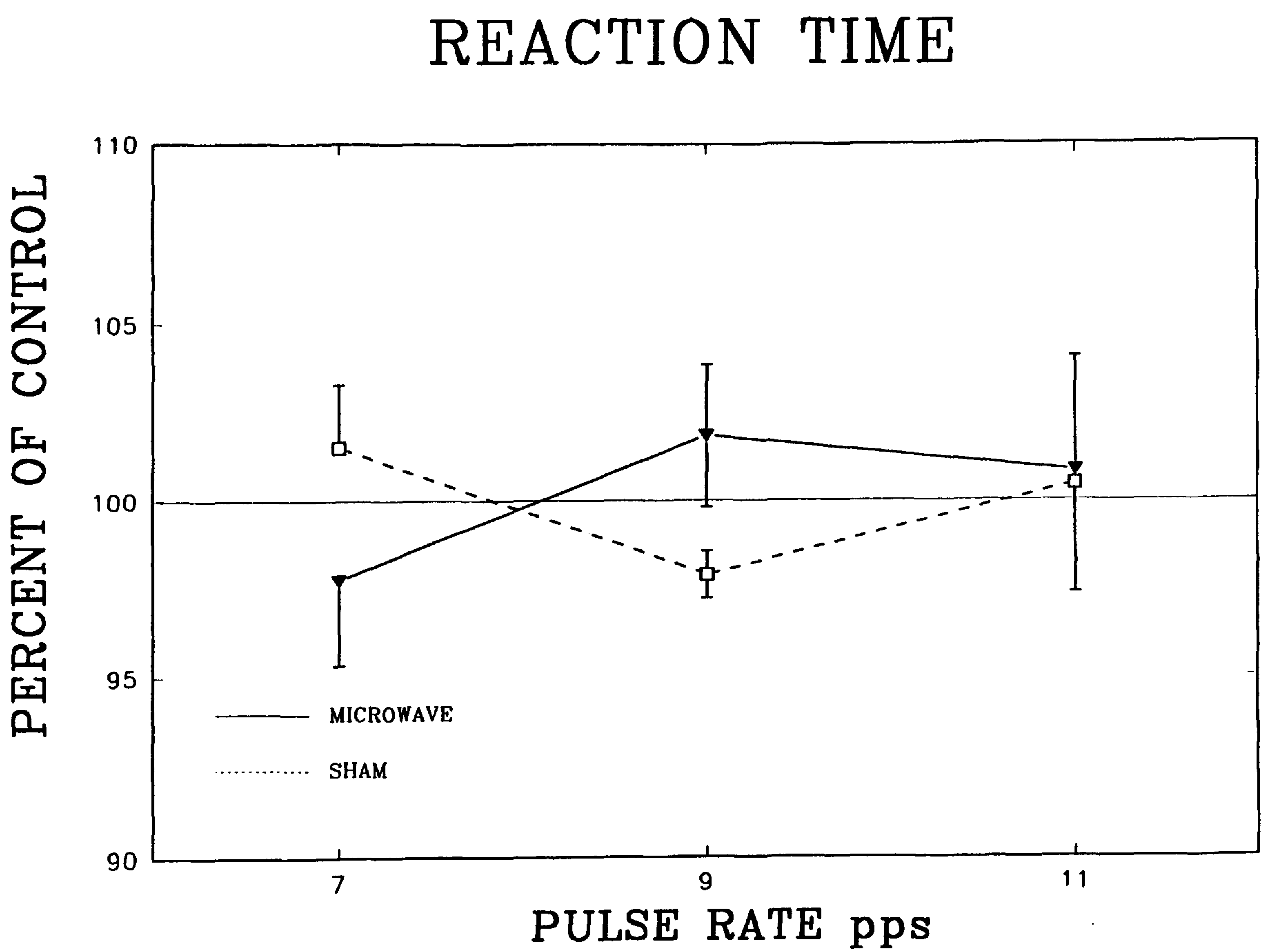

Figure 7. *Mean reaction time (± SEM) to the green light as a percentage of baseline reaction time.*

A second interpretation of the results of this study suggests that the high average SAR in the head may have simply stimulated behavioral thermoregulatory mechanisms. Stern (15) has pointed out that microwave-induced changes in behavior may reflect an animal's normal behavioral thermoregulation, which may not be compatible with lever responding for food. Behavioral thermoregulation might simply be an attempt by the animal to move to a cooler environment, which is likely incompatible with the trained behavior used in this study.

Additional evidence is needed to ascertain the likelihood of either hypothesis. We can be certain, however, that microwaves at the SAR levels used in this study did not seriously debilitate the monkeys. The lack of effect on reaction-time performance confirms this. While response rates on the lever during the red stimulus declined, the monkeys' ability and time to respond to the green light for food pellet reward as compared to baseline performance and sham exposures did not change. The postreinforcement pause time also did not change. This suggests that whatever the mechanism of action of microwaves, it is selective on different components of behavioral performance and does not simply cause a generalized malaise.

From this study, we can say that the threshold for exposure of the head to pulsed microwaves lies between 16 and 26 W/kg. The threshold for changes in behavioral performance during whole-body exposure to microwaves has been reported to be near 4 W/kg. The safety standards (1,2) employ a safety factor of 10 placing the maximum permissible SAR at 0.4 W/kg. The safety standards also employ a localized maximum SAR in any 1 g of tissue at 8 W/kg. The threshold range determined in this study for a localized exposure to the head to produce a behavioral effect of 16 to 26 W/kg suggests that the 8 W/kg safety standard does not provide a safety factor of 10. Additional experiments should be conducted with localized exposures to other parts of the body and at other microwave radiation frequencies to assess the adequacy of the current safety standard.

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